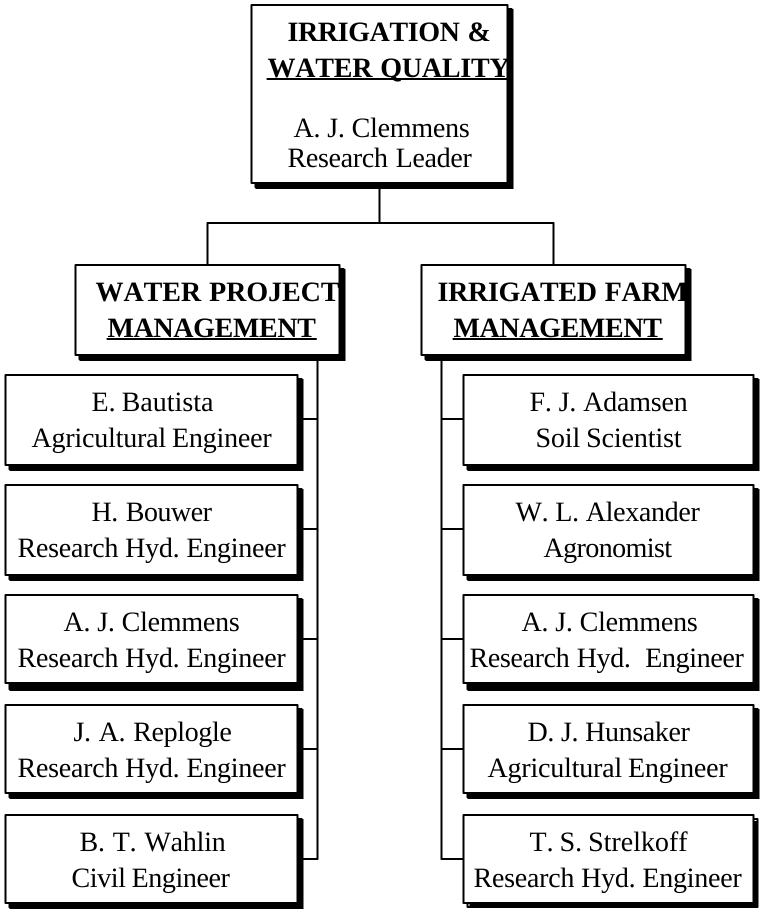
I&WQ Mangement Unit

I&WQ Organization



Mission

The mission of the Irrigation and Water Quality Research Unit is to develop management strategies for the efficient use of water and the protection of groundwater quality in irrigated agriculture. The unit addresses high priority research needs for ARS's National Programs in the area of Natural Resources & Sustainable Agricultural Systems. The unit primarily addresses the Water Quality and Management National Program. It also addresses the application of advanced technology to irrigated agriculture.

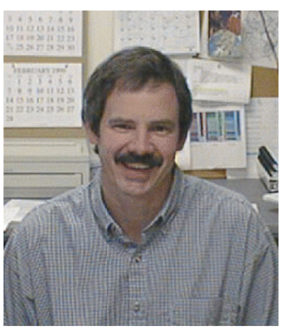
I&WQ RESEARCH STAFF

FLOYD J. ADAMSEN, B.S., M.S., Ph.D., Soil Scientist
Management practices that reduce nitrate contamination of groundwater while maintaining crop productivity; application of 100% irrigation efficiency; winter crops for the irrigated Southwest that can be double-cropped with cotton; contributions of natural and urban systems to nitrate in groundwater.

WILLIAM L. ALEXANDER, B.S., M.S., Agronomist
Drip and sprinkler irrigation systems; flood irrigation on field crops; all aspects of vegetable crops, particularly drip irrigation, chemigation, and pest control.

EDUARDO BAUTISTA, B.S., M.S., Ph.D., Agricultural Engineer
On-farm irrigation system hydraulic modeling; hydraulic modeling of irrigation delivery and distribution systems; control systems for delivery and distribution systems; effect of the performance of water delivery and distribution systems on-farm water management practices and water use efficiency; integrated resource management and organizational development for irrigated agricultural systems.

HERMAN BOUWER, B.S., M.S., Ph.D., P.E., Chief Engineer and Research Hydraulic Engineer
Water reuse; artificial recharge of groundwater; soil-aquifer treatment of sewage effluent for underground storage and water reuse; effect of groundwater pumping on stream-flow, surface water-groundwater relations.



ALBERT J. CLEMMENS, B.S., M.S., Ph.D., P.E., Laboratory Director, Research Leader for Irrigation and Water Quality, and Supervisory Research Hydraulic Engineer
Surface irrigation system modeling, design, evaluation, and operations; flow measurement in irrigation canals; irrigation water delivery system structures, operations management, and automation.

IRRIGATED FARM MANAGEMENT ANALYTICAL LABORATORY

K. Johnson, S. Colbert, and J. Askins, Physical Science Technicians

Following is a description of the functions of the Irrigated Farm Management (IFM) Analytical Laboratory. The IFM Lab is staffed by the three physical science technicians listed above.

High performance liquid chromatography (HPLC) is used to analyze nitrate and other anions in soil samples. The computer was given network capability for future backup facilitation and data access. Methods for data aquisition were revised as the detector was changed and as different ions were to be analyzed.

The autoanalyzer, a system utilizing colorimetry to determine nitrate and ammonia content of water samples and extracts of soil samples, was run and maintained. The need to dispose a hazardous substance, cadmium, in a coil used by the instrument, was discovered and addressed. The software has been updated to a more powerful Windows based system.

The laboratory has been determining total elemental carbon and nitrogen from soil samples for many years. The system was upgraded in 1997 to include the analysis of C^{13} and N^{15} on the isotope ratio mass spectrometer. Samples also have been run on this machine for groups other than IFM. New software required development of a new protocol. Fine-tuning of the instrumentation required much research and telephone assistance from the company that manufactured the instrument and created the software.

In addition to running and maintaining instruments, research technicians process data and address the precision of the data. Good precision testing alerts the operator to the necessity of a rerun and informs scientists of data reliability. Technicians also weigh soil samples, collect samples in the field, help with irrigation and other field work, write and update protocols for both reference and training, count seeds, and perform numerous other duties as needed. Combining and summarizing data from HPLC, autoanalyzer, and weighings were expedited by creating macros in a spreadsheet. One of the technicians will be sent for training in running the atomic absorption spectrometer, soon to be moved into this laboratory.

A short term goal is to have data from the weighing and the instrumental analyses as well as their summary available electronically, and progress has been made in this direction.

IRRIGATED FARM MANAGEMENT

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IRRIGATED FARM MANAGEMENT

MISSION

To develop irrigation farm management systems for arid zones that integrate year-round crop rotational strategies with best management practices (BMPs) for water, fertilizer and other agricultural chemicals. These systems will be environmentally sustainable, protect groundwater quality, and be economically viable.

STUDIES ON CONSUMPTIVE USE AND IRRIGATION EFFICIENCY

D.J. Hunsaker, Agricultural Engineer; and A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Effective irrigation management provides the timely and correct amount of water consistent with the crop water demands, soil conditions, crop production goals, and environmental quality goals. Irrigation efficiency (IE) is a term often used to describe the effectiveness of irrigation, where IE is defined as the ratio of the average depth of irrigation water that is beneficially used to the average depth of irrigation water applied. Beneficial uses include crop evapotranspiration (ET_c), salt leaching, frost protection, etc. General measures that can be taken to improve surface irrigation efficiencies include increasing the uniformity of the water applied, reducing deep percolation and surface runoff, and improving the control of application depths. However, proper irrigation management is a vital requirement for attaining the optimum irrigation efficiency of the system. Thus, the ability to predict actual daily crop water consumption, or ET_c, is of major importance.

A practical and widely used method for estimating actual ET_c is the crop coefficient approach, which involves calculating a reference crop evapotranspiration (ET) with climatic data: ET_c can then be determined by multiplying the reference ET with an appropriate crop coefficient (K_c). The Food and Agricultural Organization (FAO) Paper 24 (FAO-24), *Crop Water Requirements*, published in 1977, has been used worldwide as a primary source for crop coefficients and related ET procedures. Recently, the FAO published FAO-56, *Crop Evapotranspiration*, a revision of FAO-24, which presents updated procedures for calculating reference and crop ET from meteorological data and crop coefficients. In addition to the single K_c model developed in FAO-24, FAO-56 also includes a dual, or basal, crop coefficient model. Here, K_c is determined on a daily basis as the summation of two terms: the basal crop coefficient (K_{cb}) and the contribution of evaporation from wet soil surfaces following irrigations or rain (K_e). When the soil surface is dry, K_c is equal to K_{cb}, assuming soil moisture is adequate to sustain full crop water use. The usefulness of the dual crop coefficient model is that it provides better estimates of day-to-day variations in soil surface wetness and the resulting impacts of irrigation frequency on daily crop water use.

FAO-56 also introduced the need to standardize one method to compute reference ET from meteorological data and thus recommended the FAO Penman-Monteith as the sole method for the calculation of grass-reference evapotranspiration (ET_o). Although FAO-56 presents generalized crop coefficient values for use with FAO Penman-Monteith ET_o, derivation of localized values based on the FAO ET_o is advisable due to the effects of local climatic conditions, cultural practices, and crop varieties on K_c or K_{cb}. In order to calculate daily crop ET by the FAO-56 dual crop coefficient approach, information on the evaporation characteristics of the soil type is also needed in additional to $K_{cb.}$ The FAO-56 procedure requires two soil drying parameters called the readily evaporable water (REW), defined as the maximum depth of cumulative soil water evaporation (E_s) from the soil surface layer at the end of the stage 1 (energy limiting stage) drying cycle, and the total evaporable water (TEW), defined as the total maximum cumulative depth of water that can be evaporated from the soil surface layer. FAO-56 presents typical values of REW and TEW for certain soil types and recommends that the effective depth of the soil evaporation layer (Z_e) used in the procedures be about 0.10 to 0.15 m. Recently, several different entities have approached the USWCL interested in new information on consumptive use of crops in the area. A particular concern is the realization that many farmers have been unable to meet a target irrigation efficiency of 85%. In addition to obtaining information on basal ET for crops, quantifying the contribution of wet-soil evaporation is particularly important since soil evaporation in excess of basal ET is sometimes included in ET_c as a beneficial use and sometimes it is not. The objective of this project is to determine the consumptive use and attainable irrigation efficiencies for crops presently produced, as well as for several new industrial crops that are being developed in the region.

APPROACH: Research is being conducted through a series of field experiments to determine crop evapotranspiration for current varieties of cotton, wheat, alfalfa, rape, lesquerella, and guayule grown under irrigation and soil conditions common in the region. Crop ET and soil evaporation during different growth stages in the season will be determined primarily with a soil water balance using neutron probes and time-domain-reflectometry (TDR) measurements, although other methods such as sap flow gauges and lysimeters also will be used when possible. Basal crop coefficients will be derived from the ET_c and soil evaporation data using the FAO-56 ET_o method calculated with local meteorological data. For each crop, K_{cb} values derived from the different experiments will be combined and used to develop crop coefficient models as a function of common time-based indexes; e.g., days past planting and cumulative growing degree days. The crop coefficient curves will then be tested to determine their effectiveness in predicting ET_c for different field conditions and years.

The FAO-56 soil evaporation parameters, REW and TEW, were derived for a clay loam soil using data collected during lysimeter studies by USWCL personnel in March-April of 1971. The experimental site was a 72- by 90-m field in Phoenix, Arizona. The flat, bare field was divided into three plots, each plot surrounding one weighing lysimeter. On March 2, 1971, two of the lysimeters and surrounding plots were irrigated with 100 mm of water. After irrigation, the lysimeter weight loss, and hence soil evaporation, as well as meteorological data, were monitored at 0.5-hour intervals for 16 continuous days and also for the 23rd and 37th days after the irrigation. In the surrounding plots, soil water contents were determined from gravimetric soil samples for the 0- to 0.10-m surface layer and from neutron probe measurements for deeper soil layers at 0.5-hour intervals starting two days after irrigation through 16 days after irrigation and also for the 23rd and 37th days after irrigation. Soil water contents for the clay loam at field capacity (FC) and wilting point (WP) are 0.34 and 0.16 m^3 m^{-3}, respectively.

FINDINGS: Figure 1 shows the average daily E_s for the clay loam soil determined from two lysimeters during March 1971 for 16 continuous days after irrigation and for the 23rd day after irrigation. Also shown in the figure are estimates of daily E_s based on the average change in soil water contents (? ?), between the 00:00- and 24:00-hour measurements of a day, calculated over the 0-0.10-, 0-0.15-, 0-0.20-, and 0-0.30-m soil layers. The data of figure 1 suggest that the total daily soil water evaporation that was measured in the lysimeters occurred from a soil layer deeper than 0.10 m. From the 4th through the 10th

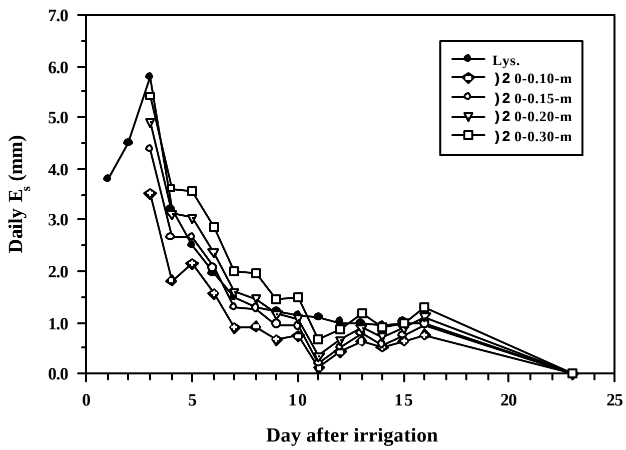

Figure 1. Average daily soil evaporation (E_s) as determined by lysimeters and the change in soil water content (? ?) calculated over 0-0.10-, 0-0.15-, 0-0.20-, and 0-0.30-m soil layers during March 1971.

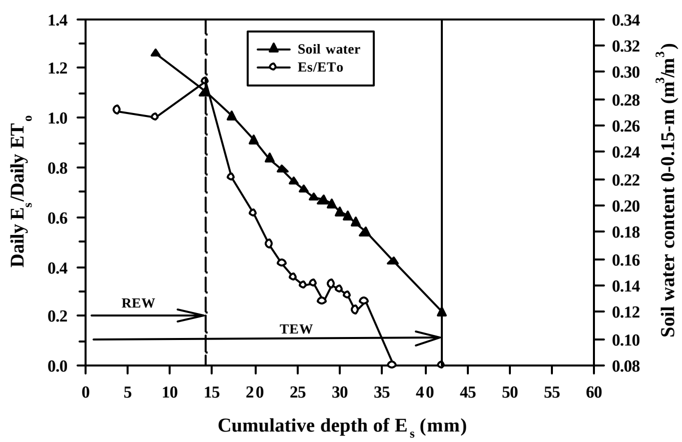

Figure 2. Ratio of daily E_s to ET_o and the soil water content within the 0-0.15-m layer with cumulative depth of E_s during March-April 1971.

day after irrigation, the daily change in soil water contents within the 0-0.15-m layer matched the daily measured E_s particularly well, whereas the daily change within the 0-0.20-m and 0-0.30-m layers was often greater than the measured E_s. From the 11th through the 16th day after irrigation, the data suggest that the soil water change within the 0-0.30-m layer was often a better reflection of the measured E_s than were the changes calculated over shallower soil layers. However, the determinations of minute daily changes in soil water contents for days occurring 11 days after irrigation and beyond (which typically were on the order of less than 1 mm) were probably subject to error arising from diurnal water loss and recovery characteristics of the surface layer, measurement inaccuracy, spatial variability, etc. Therefore, in the following evaluation of the REW and TEW parameters, it was assumed that the effective depth of surface evaporation layer (Z_e) for the clay loam soil was best represented by the 0.15-m layer.

Figure 2 shows the ratio of the daily E_s to daily ET_o for each of the 16 days following irrigation, plus those for the 23rd and 37th days after irrigation, plotted as a function of cumulative depth of E_s. The figure also shows the decline in soil water contents within the 0-0.15-m layer from the 2nd through the 37th day after irrigation. Note that cumulative evaporation between the 16th and 23rd day and between the 23rd and 37th day after irrigation was estimated from the change in soil water contents within the 0-0.15-m depth. Early in the drying cycle, when the surface layer was moist, water evaporation occurred at a rate close to the potential rate, as reflected by the near 1:1 ratio of E_s to ET_o. This stage of evaporation, referred to as the stage 1 drying cycle, occurred during the first three days after the irrigation. Therefore, it can be inferred that REW for this soil is about equal to the 14 mm of cumulative E_s during the first three days of drying. As the soil layer dried further, the rate of evaporation decreased relative to the evaporative demand until it reached a very low rate (. 0 mm on the 23rd day after irrigation). Although there was no soil evaporation on the 23rd day after irrigation, the soil layer had dried from 0.18 m^3 m^{-3} on the 16th day to 0.16 m^3 m^{-3}, the wilting point, on the 23rd day. At that point, the estimated total cumulative evaporation was 36 mm. On the 37th day, the soil water content of the surface layer had declined to 0.12 m^3 m^{-3} and the TEW, 42 mm, had essentially been reached. In most soils, evaporation can continue to dry the surface layer to a water content below wilting point. An approximate estimate of TEW is obtained by multiplying the depth of the soil layer by the difference between the field capacity soil water content and the water content halfway between the wilting point and the oven-dry point. For example, the calculation based on the FC and WP of our clay loam soil for a 0.15-m soil layer would result in an estimated TEW of 39 mm, close to the TEW derived in the analysis.

FAO-56 procedures were used to derive and partition the seasonal water consumption for a commercial cotton grown on a sandy loam in central Arizona during 1994. Using the FAO-56 approximations, the values determined for REW and TEW for this soil type were only 9 mm and 19 mm, respectively. As shown in Table 1, soil evaporation represented about 7% of the total crop ET contributed solely from irrigation water. An additional 88 mm of ET were contributed from in-season and pre-season precipitation. About one-third of the seasonal precipitation, which occurred primarily during the early portion of the season before full crop cover, evaporated from the soil surface. Of the total 1162 mm of ET consumed by the crop, 9% was evaporation from wet soil conditions.

Table 1. Water consumption for a grower's cotton field in 1994.

	Irrigation water	In-season precip.	Pre-season precip.	Total
Basal ET	996	48	13	1057
Soil E_s	78	27	n/a	105
Total crop ET	1074	75	13	1162

INTERPRETATION: Findings from our evaluations of a grower's field indicated that evaporative water losses from the soil need to be considered in determining crop water use and irrigation efficiencies. This was further illustrated by the 1971 lysimeter data presented above, which showed that over 40% of the 100 mm of water applied to a bare clay loam soil was evaporated from the surface layer. In arid or semi-arid conditions, soil water evaporation, particularly following pre-plant and early season irrigations, can therefore represent a significant amount of water loss above the basal crop water requirement. Information to quantify crop ET and soil evaporation more accurately will continue to be developed in this project.

FUTURE PLANS: Once appropriate basal crop coefficient curves and soil drying parameters have been developed, they will be incorporated into the FAO-56 dual crop coefficient model, which can then be used as an effective irrigation scheduling tool for determining ET_c and soil evaporation on a daily basis. The FAO model for ET also will provide a means to estimate on-farm irrigation efficiencies on a single irrigation basis, as well as for the entire season.

COOPERATORS: Rick Allen, Professor, Utah State University; Ed Martin, Irrigation Specialist, The University of Arizona; Huanjie Cai, Professor, Northwest Agriculture University, Yangling, Shaanxi, China.

DEVELOPING GUIDELINES FOR "FERTIGATION" IN SURFACE-IRRIGATED SYSTEMS

F. J. Adamsen, Soil Scientist; D. J. Hunsaker, Agricultural Engineer; and A. J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Applying fertilizer through irrigation water, when properly done, can be a highly effective fertilizer management practice. This method of fertilizer application, "fertigation," offers certain advantages compared to conventional field spreading or soil injection techniques, such as reduced energy, labor, and machinery costs. Moreover, it allows growers to apply nutrients in small amounts throughout the season in response to crop needs without the potential crop damage or soil compaction caused by machinery-based application methods. Although fertigation is more commonly associated with microirrigation and sprinkler irrigation systems, injecting nitrogen (N) into irrigation water has become increasingly frequent and widespread among surface irrigation growers in the western United States. However, unlike pressurized irrigation systems, which are designed to apply controlled and precise amounts of water to the field, application of water by many surface irrigation systems can be highly nonuniform and is often subject to excessive deep percolation and surface water runoff. Consequently, N-fertigation through surface irrigation systems may result in fertilizer distributed unevenly throughout the field and potential nitrate-nitrogen (NO_3-N) contamination of groundwater through deep percolation and of surface water through tail water runoff. Because the environmental fate and distribution of nitrogen applied in surface irrigation water has not been studied extensively in the field, adequate N-fertigation management guidelines have not been developed.

APPROACH: The primary objective of the research is to develop information that will lead to best management practices (BMPs) for N-fertigation through surface irrigation systems. The project will derive this information through a series of extensive farm-scale field experiments conducted on representative surface irrigation systems commonly used in the western U.S. The measurement objectives include the determination of the spatial distribution and seasonal variation of N within the field, and the relative potential of groundwater and surface water contamination as a function of the timing and duration of N injection during the irrigation event. Irrigation water application distribution also will be determined for each irrigation. Ultimately, the data derived from this project will be used to incorporate chemical fate and transport components into existing soil water and surface irrigation simulation models, which once validated, will allow more comprehensive evaluation of fertigation practices and an expansion of BMPs for conditions and irrigation systems other than those encountered in this project.

In 1999, two simulated fertigation events were conducted on cotton grown in furrowed level basins at the Maricopa Agricultural Center (MAC). The first fertigation was conducted following cultivation which provided a rapid infiltration rate and a high degree of surface roughness. The second event was carried out during the third irrigation following cultivation which provided lower infiltration rates and less surface roughness than the first fertigation. During both events, potassium bromide (KBr) was injected into the water stream. The treatments for the experiments were injection during 100%, first 50%, and last 50% of the irrigation. Water was applied to five furrows in a 185 m long field. Soil samples were taken before and after the event to a depth of 1.2 m in the turn around area at the head of the field and every 30 m along the run. In the turn around area, two samples were taken and at the sampling locations along the length of run samples were taken from two adjacent cotton beds and from the furrow bottom of a wheel and non-wheel furrow. Samples were analyzed for bromide concentration. Irrigation parameters measured were advance and recession times, flow rate, and surface water depth.

FINDINGS: Figure 1 shows the average field distribution of the change in bromide concentration within the 0-300 mm soil depth for each of the three fertigation treatments following the first irrigation. The bromide concentration for our 100% fertigation treatment was depressed at the head end of the basin (reflecting possible deep percolation losses), peaked at a distance of 60 m, and then decreased slightly with distance towards the end of the basin. The distribution of bromide that was applied during only the first 50% of the irrigation followed a trend quite similar to the bromide distribution for the 100% fertigation treatment. There was not an apparent increase in bromide level at the far end of our level basin. In contrast, the bromide pattern that resulted when fertilizer was injected during just the last 50% of the irrigation showed strong downward trends with distance.

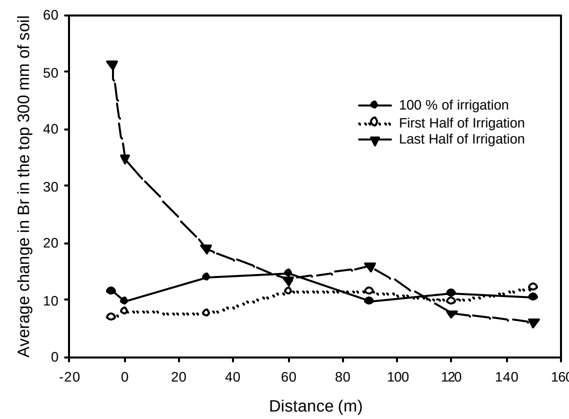

Figure 1. Distribution of the change in bromide concentration in the top 300 mm of soil with distance after application of bromide during 100%, the first 50%, and the last 50% of the irrigation of a level basin.

In level basins, a controlled volume of water is applied from one end or one corner of a basin, completely enclosed with perimeter dikes to prevent runoff. Figure 2 shows a relatively uniform infiltrated depth distribution for a level basin irrigation, estimated by a simple advection (volume balance) model. This example illustrates a situation in which applying fertilizer during 100% of the irrigation event may be the best fertigation option. Injecting fertilizer during just the first 50% of the irrigation may result in poor fertilizer distribution uniformity throughout the basin, as suggested by the rather large differences between the infiltrated depths at the far end versus other areas of the basin after 50% of the irrigation had been applied. Also, deep percolation losses would be proportionately high with this fertigation application, since all deep percolation water is contributed just from water applied during the first 25% of the irrigation. In contrast, adding fertilizer during just the last half of the irrigation would result in too much N at the front end of the basin and too little at the far end, although there would be no N lost due to deep percolation. Applying fertilizer during 100% of the irrigation would result in a relatively even distribution of N in the root zone with a small portion of the total N leached with deep percolation (as represented by the area underneath the deep percolation curve).

INTERPRETATION: The example of figure 2 suggests that if irrigation uniformity is relatively good, adjustment of the timing and duration of fertigation, as opposed to continuous injection during the entire irrigation, may not be warranted. However, it is important to point out that fertigation recommendations derived using modeling techniques, e.g., the simple advection model used above, are highly speculative, since dispersion, adsorption, and desorption processes are either ignored entirely in the models or models have not been validated based on actual field conditions. In practice, fertigation recommendations are expected to vary widely, subject to the myriad of combinations of irrigation specifics; e.g., the split between the deep percolation and runoff, relation between advance and opportunity time, soil texture, changing infiltration and surface roughness characteristics, cultural practices, etc. In order to develop models which adequately describe and predict solute transport processes during fertigation of surface systems, comprehensive field studies must be undertaken to develop data over a wide range of irrigation systems, practices, and field conditions.

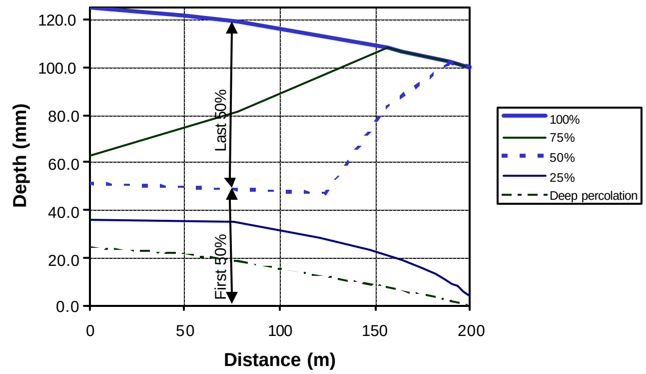

Figure 2. Cumulative infiltrated depth with distance after 25%, 50%, 75%, and 100% completion of the irrigation and deep percolation with distance for a level basin irrigation system.

The lines in figure 2 represent the infiltrated depth of the first, second third and fourth quarters of an irrigation applied to a 200 m long level basin. It is interesting to note that some similarity exists between the pattern of bromide distribution for a particular fertigation treatment in our level basin experiment (Fig. 1) and the predicted pattern based on the infiltrated depth distribution estimated with different field conditions for the level basin of figure 2. Our preliminary research results on the timing and duration of fertigation during the irrigation event suggest that significant progress can be made towards defining the best fertigation management strategies for surface irrigation systems. However, technology in this area is underdeveloped and progress has been greatly hindered by a lack of sufficient field data.

FUTURE PLANS: Analysis of remaining soil samples will be completed. Irrigation data will be analyzed using the software package EVALUE to estimate average field infiltration and to estimate Manning n values for surface roughness. Pending additional outside funding, similar data sets will be developed for unfurrowed level basins, furrowed and unfurrowed sloping borders with and without runoff over a variety of soil types and lengths of run in Arizona and California. When completed, the data sets will provide a sufficient range to develop fertigation guidelines for a large portion of the surface irrigated acreage in the western United States.

COOPERATORS: Mr. Donald Ackley, Program Coordinator, Coachella Valley Resource Conservation District, Indio CA; Dr. Bob Roth, station director, Maricopa Agricultural Center, Maricopa, Arizona.

USE OF A LOW COST COLOR DIGITAL CAMERA TO MEASURE PLANT PARAMETERS

F. J. Adamsen, Soil Scientist; P. J. Pinter, Jr., Research Biologist; T. A. Coffelt, Research Geneticist; and E. M. Barnes, Agricultural Engineer

PROBLEM: The number and timing of flowers a plant produces is of interest because it can be an important factor in determining yield. The time required manually to count flowers in the field makes it difficult to carry out large studies involving flower numbers. It is possible to detect flowers on plants which are not obscured by leaves and stems in digital images. Documenting plant parameters such as crop senescence rates, fertility levels, insect damage, salinity problems, disease and nematode damage, etc., which result in changes in plant color, is often difficult due to the need for frequent sampling during periods of rapid change and the subjective nature of visual observations. Digitized images of crops should show temporal changes in the greenness of crop plants as well as differences related to treatments. Low cost digital cameras, which are available in the market, provide an easy and inexpensive method of obtaining digital images of plants that can be analyzed for a number of plant parameters. The objectives of this work are (1) to develop the methodology needed to use digital color images for documenting crop senescence rate, flowering, and other plant parameters, and (2) to apply the methodology to improve nitrogen and water management practices.

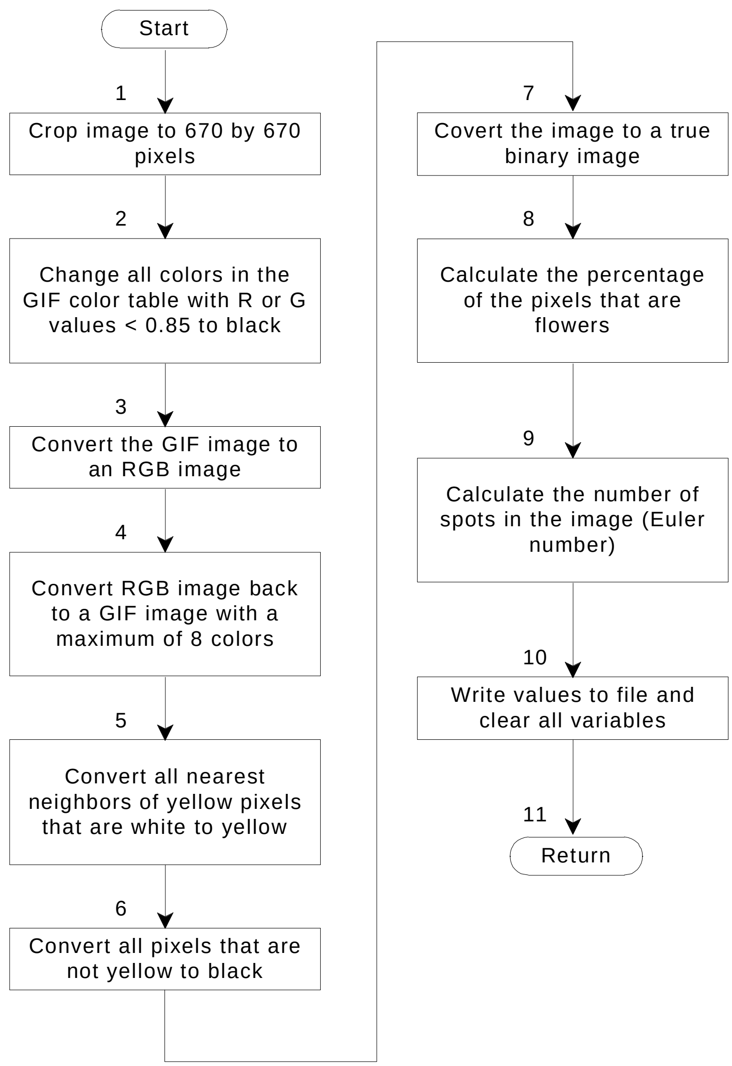

Figure 1. Flow diagram of main automated image processing loop for flower counting.

APPROACH: A digital camera which costs less than $1000 was used to obtain images of lesquerella (*Lesquerella fendleri*) in a field experiment of fertility and seeding rate at the University of Arizona's Maricopa

Agricultural Center (MAC), near Phoenix, Arizona. The experimental design was a complete factorial of three fertilizer rates and four seeding rates. Fertilizer as ammonium sulfate at rates of 0, 60, and 120 kg ha^{-1} was applied at flowering. Digital images of the plots were taken periodically from mid-March to early-June using a color digital camera. Images were acquired between 1030 and 1300 h MST. The camera had a 1024 by 768 pixel resolution and twenty-four bit color resolution. The method described in Fig. 1 was used to count the number of flowers in the images. The first step in processing the images was to crop the image so that it showed an area of 1m by 1m. All pixels with yellow color were identified, and spots of yellow color were then counted (Fig. 2). Two indices were developed. The simplest was the number of pixels in the image identified as flowers and the second was a count of the number of spots. Thus far, the number of flower pixels has been the most useful.

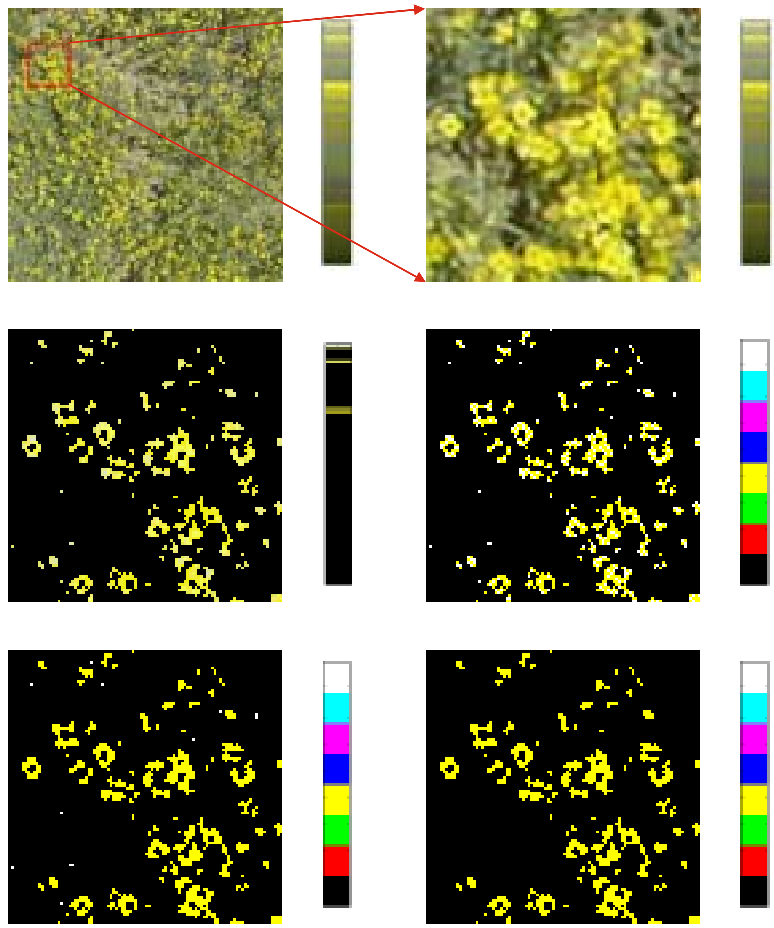

Figure 2. Results of image processing on the image from Plot A on April 15, 1997; (a) cropped image; (b) area of cropped image outlined in red; (c) after color depletion; (d) after color remapping; (e) after search for yellow spots; (f) after elimination of non-yellow pixels.

FINDINGS: Flowering responded to the amount of fertilizer applied but not to seeding rate (Fig. 3). Peaks in flowering occurred following irrigations through March and April (Fig. 3). In May as the crop approached maturity, flowering responded to irrigation only at the lowest nitrogen level (Fig. 3a). In plots where fertilizer was applied at flowering, flower production continued at a higher rate than in the unfertilized plots which received only preplant fertilizer (Fig. 3). Peak flowering occurred on March 26, 1998, for the 0 N treatment but not until April 16, 1998, for both the 60 and 120 kg N ha^{-1} treatments. Peaks in flowering were less pronounced and the decline in flowering was more abrupt in the 60 and 120 kg N treatments than in the 0 N treatment. By June 4, 1998, the last date that images were acquired, all of the treatments ha essentially stopped flowering. Treatment means of % flower pixels for each date and the sum of % flower pixels from March 19, 1998, through each date were regressed against the treatment means of yield. The coefficient of determination for the regression was then plotted against date (Fig. 4). Flowers formed in March and early April appear to have little impact on yield. The r^2 values for this period are less than 0.30 while the r^2 values from the first three weeks in May were all 0.85 or higher. The largest r^2 for a single date was 0.95 for May 14. For sums of % flower pixels, the regression with yield never provided as good a fit as the single dates from the first three weeks in May. The drop off in r^2 values for single date regressions after May 14, 1998, occurs because there is no difference between treatments in flowers after mid-May while there are differences in yields between treatments. Daily high temperatures in late May typically approach 40° C and may reduce flowering.

INTERPRETATION: The flowering data shows that while flowering lasts for twelve weeks, there is a four to six week period beginning 180 d after planting that has the greatest influence on yield. The number of flowers present at the beginning of flowering reflect the emergence and survival of seedlings, but the early flowers do not reflect yield. Substantial growth occurs after fertilization at the start of flowering thus much of the seed is formed later in the growing season.

The data suggest that fertilizer application at flowering may not be the best nitrogen management strategy. Applying fertilizer to achieve growth prior to flowering should shorten the flowering period and take better advantage of the first flush of flowers formed by having a larger healthier plant. However, an impediment to early fertilizer application is the slow emergence and early growth of lesquerella. Because of slow emergence, it was necessary to make four irrigations for stand establishment. When the crop is grown with surface irrigation, as in this case, minimum water applications were 50 mm. In this case, that means at least 200 mm of water was applied when the crop was not able to use it. Applying 200 mm of water to a fertilized crop often results in leaching of nitrate from preplant applications below the root zone.

While not shown directly by this study, the flowering data suggests that the reason lesquerella responds to planting date is related to growth of the plant before flowering begins. Earlier planting dates allow for more vegetative growth, resulting in larger plants when flowering begins in the spring.

Results from this study validate the method proposed by Adamsen et al. (in press) for using a digital camera to monitor flowering in a crop. They also show that by monitoring flowering, critical flowering times can be identified. This can lead to altering production practices, such as earlier application of fertilizer, to maximize yield and smaller more frequent irrigations to reduce the effects of short term water stress. The cessation of flowering in conjunction with weather data should be useful in determining precise harvest dates.

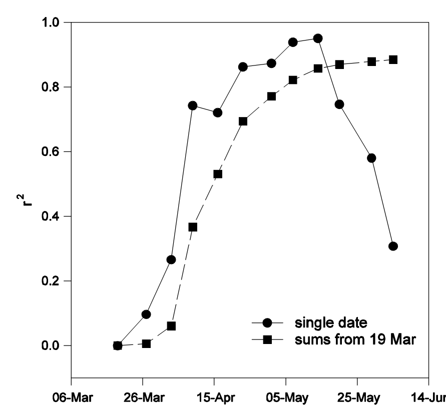

Figure 4. Change in coefficients of determination for regressions of treatment means of percent flower pixels against treatment means of yield for single dates and for the sums of percent flower pixels across dates beginning on March 19, 1998.

FUTURE PLANS: Flowering data will be developed for rape, crambe, alfalfa, and vernonia. Rape flowers are similar to lesquerella flowers in color and crambe flowers are white. Vernonia and alfalfa flowers are purple to pink in color but appear blue in digital images. These crops should test the applicability of the general methodologies developed for lesquerella. If this effort is successful, the feasibility of counting flowers on other crops such as cotton will be evaluated. Greenness indices will be developed for sorghum and alfalfa. The use of greenness indices with forage crops can help assess the effects of various treatments on regrowth and harvest date. The relationships of greenness indices and flower number with fertility and water management will be developed. Once these relationships are developed the will be used to develop improved water and fertilizer management practices.

COOPERATORS: Dr. John M. Nelson, The University of Arizona Maricopa Agricultural Center; Dr. James M. Krall, University of Wyoming Research and Extension Center, Torrington, Wyoming.

SURFACE IRRIGATION MODELING

T.S. Strelkoff, Research Hydraulic Engineer; and
A.J. Clemmens, Supervisory Research Hydraulic Engineer and Laboratory Director

PROBLEM: Throughout the irrigated world, water is applied to fields unevenly and excessively, leading to wastage, soil loss, and pollution of surface and groundwaters. Computer modeling would allow rapid evaluation of physical layouts and operation in a search for an optimum. But most models are limited to single furrows or border strips and basins with zero cross-slope and a uniformly distributed inflow at the upstream end. Yet large basins are usually irrigated from a single inlet. The flow spreads out in all possible directions, and any one-dimensional simulation must be viewed as a very coarse approximation. A non-planar basin surface influences the flow as well. An irrigation stream concentrated in the lower-lying areas can significantly affect infiltration uniformity. Only a two-dimensional model can simulate these factors.

While a one-dimensional approach is suitable for furrows, in real fields, flows in neighboring furrows of a set are often coupled through common head and tail-water ditches. Tailwater from a fast furrow can enter a slower furrow from its tail end and modify its ultimate infiltration profile. To appreciate the effects of such coupling fully, simulation of interconnected furrows is necessary.

Irrigation management can influence the quality of both surface and ground waters as well as of the field soils. Irrigation streams can be of sufficient power that soil boundaries erode, with the material entrained into the stream and transported downfield, reducing soil fertility upstream. Farther downstream, as infiltration reduces the discharge or as the result of slope reduction, part of the load, perhaps only the coarse fractions, might deposit back onto the bed. Or else, entrained material can run off the field, introducing turbidity into drainage water or deposit in quiescent areas, to the detriment of aquatic life.

Chemigation introduces agricultural chemicals into the irrigation water. Alternately, initially clean irrigation water picks up agricultural chemicals and naturally occurring minerals, some toxic, from the surface of fields and from contact by percolation through the porous soil medium. Nitrogen, phosphorus, and heavy metals, for example, brought to farm fields in agricultural operations and naturally occurring chemicals, such as selenium, can be transported to surface or subsurface water supplies by irrigation water, to the detriment of both human consumers of the water resource and wildlife dependent on the receiving water bodies. Nutrients or pesticides adsorbed to eroded soil in irrigation tailwater is an important example.

APPROACH: The objective of current work is validated computer simulation models for providing quick responses to a wide variety of "what-if" situations. For example, the trade-offs between irrigation efficiency and uniformity, on the one hand, and soil loss, on the other, could be explored. Recommendations could then be made on the basis of environmental considerations as well as water conservation and crop yield. Funding for this effort is provided in part by the Natural Resources Conservation Service.

For one-dimensional single-furrow, border, or basin simulation, user-friendly, menu-driven data input and output graphs and text are linked to a simulation engine based on the universal laws of hydraulics applied implicitly in fully nonlinear form. Constants in commonly accepted empirical equations for infiltration, roughness, and soil erosion are entered as input. The computer model, SRFR, is based on this approach.

Two-dimensional simulation is also based on hydraulic principles. Under the assumption of flow velocities small enough to neglect accelerations, force components in each of two mutually perpendicular directions on the field are in equilibrium. The resulting parabolic partial differential equations, solved implicitly by locally linearized finite differences in the two directions and time, yield a wave-like solution encompassing both wet and dry areas of the field. A similar but one-dimensional approach, treating wet and dry cells uniformly, is applied to multiple coupled furrows.

Erosion, transport, and deposition of irrigated soil is too complex to simulate on the basis of general physical principles alone. Currently, it is *fundamentally* an empirical science, in which the trend in recent years has been towards ever more general relationships, containing as much general physics as possible. Many conceptual models of parts of the total process have been proposed in order to avoid pure empiricism, but these are only partially convincing, with researchers intuitively leaning toward one or another. The measures of a good predictive relationship or procedure are its generality with respect to different soils and different irrigation conditions, and ability to predict soil transport at different locations in a furrow, especially in the tailwater runoff, at all times during the irrigation.

FINDINGS: The SRFR 4.00-series surface-irrigation simulation model has been released for downloading through the U.S . Water Conservation Laboratory (USWCL) web site (also newly available at this site are the earlier programs, BASIN and BORDER, design and management aids for level-basin and border-strip irrigation). In addition to the wide variety of surface-irrigation techniques and scenarios that can be simulated with this menu-driven graphics-oriented program, a preliminary erosion component is available to cooperating researchers. Figure 1, drawn from the animation displayed by SRFR during a simulation, illustrates typical behavior of the transport-capacity function and resultant sediment loads at one instant of time (61 minutes into the irrigation). Note the lengthy region behind the stream front in which the transport capacity and detachment are zero. Because of upstream infiltration, the flow rate is so small there that the boundary shear is below the threshold for entrainment. Far upstream, the sediment load grows the fastest at the clear-water inflow, where the transport capacity is a maximum

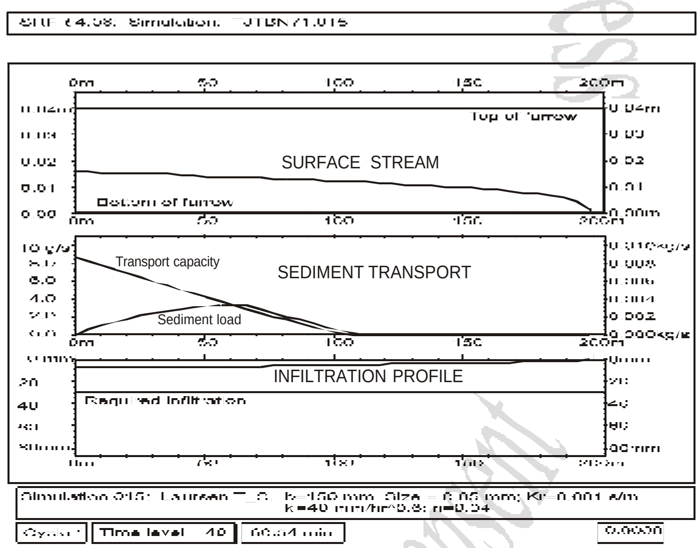

Figure 1. Frame of animated output of SRFR simulation – profiles of surface stream depth, sediment load and transport capacity, and infiltrated depths; time=61 min

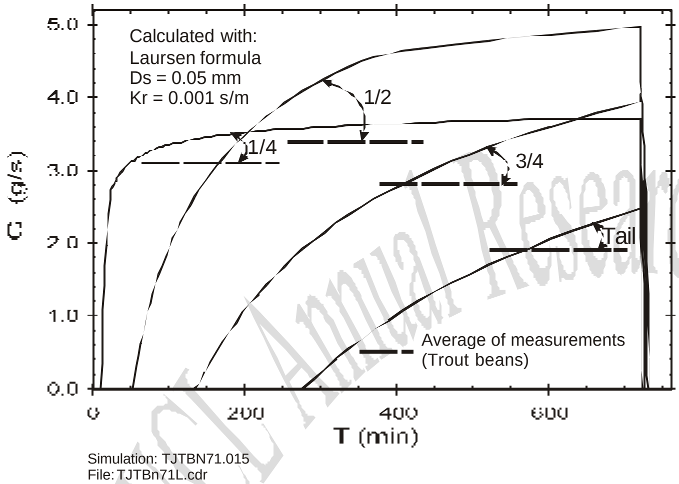

Figure 2. Comparison of simulated sediment transport hydrographs at furrow quarter points with averages from measured Trout bean data of July 1, 1994. Site-specific Kr=0.001s/m, t_c=1.2 Pa. Laursen (1958) transport-capacity formula in effect. (Strelkoff and Bjorneberg, 1999)

and the existing sediment load zero. With distance downstream, the transport capacity decreases due to infiltration, and the sediment load increases due to upstream entrainment; both factors lead to reductions in further growth in the load. Eventually, though, transport capacity *is* exceeded, and some of the load starts to deposit back onto the bed. Finite fall velocities are seen in the "super-saturated" concentration of sediment evident in the figure.

Strelkoff and Bjorneberg (1999), utilizing in SRFR's erosion module the Laursen (1958) formula with a representative particle size midrange in the field-measured mix, got a reasonable match between results of the simulation and Idaho field data, as in Figure 2. They also found that the Yang (1973) and Yalin (1963) formulas (WEPP) greatly overestimated the capacity of furrow flow to carry sediment, with consequent under-prediction of deposition back to the lower reaches of the furrow.

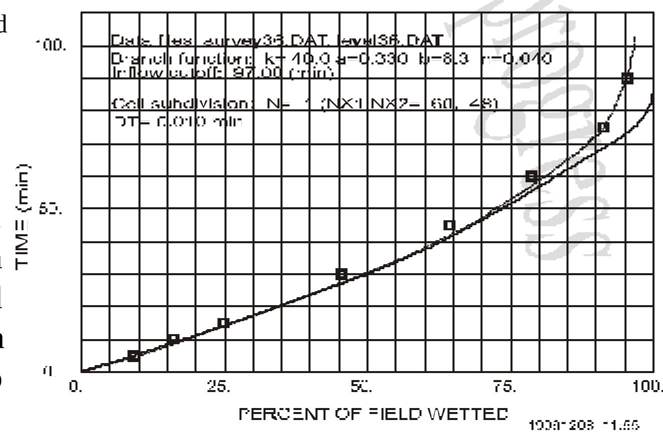

Figure 3. **Advance curves –**
Squares: measured;
Dotted: computed, with surveyed field elevations;
Solid line: computed, for a plane, level field.

The two-dimensional simulation model was tested against field measurements obtained in a 3 ha (7 acre) basin at the Gila River Farms, irrigated from the center of one side. Monitoring of water levels in 26 locations and a land-level survey allowed estimation of the soil infiltration characteristics, represented by a power law of time in the early stages, branching to a constant infiltration rate after 4 hours of wetting. Assumption of the reasonable Manning n=0.04 yielded the results shown in Figure 3. Predictably, the irregular field surface requires additional time to wet the high spots; in fact, it is apparent that some 4% of the field area is so high that with the given cutoff, at 97 minutes, it is never wetted. The computations appear to agree with field data to within measurement errors.

INTERPRETATION: The growing body of simulation software is finding users in the national and international irrigation community for design, management, and evaluation of surface irrigation. It is likely that studies of the interrelationship among distribution uniformity, standard deviation of surface elevations, and inflow rate will provide a useful adjunct to current design software. Predictions of soil erosion, transport, and deposition are significantly less accurate than predictions of hydraulic performance, but the influence of design and management is easy to see, so that these aspects also can be taken into account.

FUTURE PLANS: In order to get a more accurate simulation of sediment transport and, in particular, for subsequent simulation of chemical adsorption to the surface areas of that sediment, the distribution of particle sizes in the sediment mix should be accounted for. For example, the extensive field work of Fernandez (1997) shows consistent decreases in sediment concentrations with irrigation time at various locations along the furrow. This suggests a supply-limited erosion event, which is, in the absence of scour-hole formation, a concept possible only in a graded mix. This is because in a cross section essentially constant with time, a homogeneous soil provided with a constant supply of, say, clean water continues to churn out sediment at a constant rate. The reductions with time noted most likely stem from the fact that gradually all of the particles which *can* be detached *are*. What remains on the bed are particles too large or heavy to be entrained, with finer ones underneath, protected from scour by the coarse layer at the soil-water interface.

Deficiencies in SRFR noted by users will be addressed, including coalescing of successive surges. As funding becomes available, the two-dimensional pilot model will be reoriented towards routine application. Increasing the allowable time step, currently very small in basins with a fine grid of soil and water surfaces, will be explored. A multiple-furrow model will be completed, and additional field verification for both the two-dimensional and the coupled-furrows programs will be sought, pending outside financial support. Long-term plans include incorporation of relationships for cohesive soils, a relatively poorly understood area in the field of sediment transport. Incorporation of soil-chemistry components is contemplated; water and soil salinities play a great role in erosion, especially in clays. Estimates should be made of the pre-wetting effect for surge irrigation. Pre-wetting phenomena have been shown to have a significant effect on detachment; but virtually all of the WEPP erosion database is for pre-wetted (rained-on) soils, which do not exhibit the violent fine-scale commotion observed at the front of a wave of irrigation water in a dry, powdery bed. Also, soil and water temperature effects on infiltration and erosion require quantification.

As funding becomes available, chemical transport and fate will be included in SRFR.

COOPERATORS: Thomas Spofford, Natural Resources Conservation Service, National Water and Climate Center, Portland OR; Luciano Mateos, and Rafael Fernandez, Instituto de Agricultura Sostenible, CSIC, Cordoba, Spain; David Bjorneberg, Rick Lentz, Robert Sojka, ARS Northwest Irrigation and Soils Research Laboratory, Kimberly ID; Thomas Trout, Water Management Research Laboratory, Fresno CA; D.D. Fangmeier, University of Arizona, Tucson AZ; Marshall English, Oregon State University, Corvallis OR; Roger Stone, Gila River Farms, Pinal County AZ.

REFERENCES:

Fernandez Gomez, R. 1997. La erosión del suelo en el riego por surcos (Erosion of soil in furrow irrigation), PhD Dissertation, University of Cordoba, Cordoba, Spain. November. 231 pp.

WATER PROJECT MANAGEMENT

CONTENTS

WATER PROJECT MANAGEMENT

MISSION

To develop tools for the management and augmentation of water supplies in arid-region water projects, particularly those associated with irrigation. This includes methodologies for measuring and monitoring water fluxes with natural and man-made systems, methods for improving control of water within distribution networks, conjunctive management of groundwater and surface water supplies, artificial recharge of groundwater, natural water treatment systems (e.g. soil-aquifer treatment), and methods for assesing the performance of water projects in terms of water quality and quantity management.

MEASUREMENT AND CONTROL OF WATER FLOW UNDER DIFFICULT CONDITIONS

J.A. Replogle, Research Hydraulic Engineer; and B.T. Wahlin, Civil Engineer

PROBLEM: There are many flow conditions that are not amenable to the use of simple flumes and weirs. Many other measurement devices and methods are more expensive, more difficult to use, or less accurate than flumes and weirs. Improvements in these other methods are needed to complement the advances with flumes and weirs. Problems of continuing interest related to pipe flows include flow profile conditioning in pipes, field applications of several flow meters to irrigation wells, and automatic regulation of flow through large irrigation outlet pipes from main canals to lateral canals.

Most delivery canal systems use pipes through the canal banks to deliver flows to farm canals. Propeller meters, end-cap orifices, Pitot systems, and ultrasonic meters placed in these pipes frequently are subjected to poorly conditioned flow profiles that compromise the meters' operation. All of these are affected by upstream pipe bends and valves. Propeller meters readily clog in debris-laden flows and usually can be inserted into trashy flows for only a few minutes. End-cap orifice meters do not work well on rusted pipe ends. Pitot systems are considered difficult to apply to discharges from wells without special wall taps and insertion ports. Inserting a standard combination Pitot-static tube, such as the Prandtl tube, into the outflow end of a pipe has been used. However, these tubes are expensive, requiring specialized manufacturing techniques not available in most machine shops. Methods to condition flows and improve the flow profiles are needed, particularly when short lengths of straight pipe precede the meter.

Fluctuating flow-rate deliveries from a main canal to a secondary canal increase the difficulty of effective irrigation and may require expensive means to monitor total delivered water volume. The same type of pipe outlets described above are being considered for retrofitting with mechanical-hydraulic mechanisms that would stabilize the discharge rate through them regardless of changes in the level of the source canal. Fluctuating flow-rate deliveries from a main canal to a secondary canal increase the difficulty of effective irrigation and may require expensive means to monitor total delivered water volume. Steady flows can use simple time clocks for total volume.

Several pipe flow metering devices are limited in their field use when applied to irrigation canals and wells for a number of reasons. Propeller meters readily clog in debris-laden flows and usually can be inserted into trashy flows for only a few minutes. Portable end-cap orifice meters do not attach well on rusted pipe ends. Ultrasonic meters are expensive. While improvements in some of these have been made, the efforts leave room for further progress.

The several ongoing objectives associated with pipe system flows are: (a) to complete papers and technical notes regarding the design and calibration of the modified Pitot system for irrigation wells that can be constructed in ordinary shop settings and the suggestions for simplifying the use of portable end-cap orifices (see previous Annual Reports); (b) to develop practical methods to achieve effective flow conditioning for flow meters installed in difficult short-pipe situations, and (c) to evaluate prototypes of clog-resistant propeller meters that have been manufactured to our suggestions.

APPROACH: Standard calibration procedures were previously completed on the end-cap orifice system. An alternate pressure tapping system was studied. This involved using a small static pressure tube (with holes drilled through its walls), similar to that used for the Pitot system described last year, to detect the pressure in the approach pipe upstream from the orifice. The tube was inserted through a grommet-sealed hole in the face of the orifice plate near the pipe wall so that the pressure sensed was that for one pipe diameter upstream from the face of the orifice. No further lab data were gathered.

A new float-operated valve that can be used in combination with a water inflated bag is proposed to be inserted under a gate, made to raise a weir, or fitted into the pipeline from a main canal to a secondary canal to maintain a desired flow level at locations. These are cross referenced to the related "Pipe-Flow" project report for the pipe flow situations. These modifications for channels will be reported herein. The objectives are to develop hydraulic flow control devices applicable where access to electricity may not be convenient and to evaluate the effectiveness of their function. This is an extension of the previously developed DACL (Dual Acting Controlled Leak) systems.

Methods to condition flow profiles in pipe outlets will include insertion of minimum contraction orifices and sidewall vanes. A special 30-inch diameter pipe facility is now ready for conducting these tests.

A meter builder in Fair Oaks, California, (Global Water) constructed and furnished two industrial propeller meter prototypes following our debris shedding design proposals. They will be tested in the 30-inch diameter pipe facility mentioned above. An ultrasonic velocity probe will be used to define this flow field.

The large pipe system has been modified to allow testing of a pipe flow control concept using a new valving and obstruction idea. The equipment will be installed into the pipe, preferably in a "kit" format that can be adapted to many field situations, and evaluated in terms of response times and flow stability.

FINDINGS: End-cap Orifice: The orifice system calibrated as expected from theory, and is more repeatable than corner tappings on a pipe of uncertain end quality. The convenience aspects of the system were demonstrated. (No new data acquisition is planned.)

Flap Gate: We expected that, as the flow in the pipe increased, the change in the pressure grade line should decrease because there would be more kinetic energy used to keep the flap gate open. However, no distinct pattern could be seen from the data. Low flows and high flows produces back pressures on the order of only 4 mm to 6 mm of water column. (No new data acquisition is planned.)

Flow Profile Conditioning: There are no new findings to report.

Propeller Meter: This has been delayed for higher priority studies. There are no new findings to report.

Pipe Flow Control System: A new DACL valving system was developed because a commercial version did not provide the needed functions. The new valve appears to be capable of all required functions but needs to be laboratory and field proven. A variety of low-cost bag products has been collected. The bag concept was tried on a small model and appeared to function well. Scaling problems have not been ruled out.

This has been started and is planned to continue. Progress includes designing and building a suitable low-cost valving system and companion pipe flow obstruction method that is ready to be tested (Fig. 1 & 2). A small model of the concept operated as hoped. The new valving equipment was not used in these tests, but had to be simulated by other means. The test facility was modified to allow testing of the control concept.

INTERPRETATION: End-Cap Orifice: This version of the end-cap orifice can be installed on well pipe outfalls without any specially drilled holes. The corner tap locations of the original version, which also did not require pipe drilling, are somewhat sensitive to poor pipe-end conditions. While this version cannot be used if the pipe is in badly eroded condition, it is somewhat forgiving. The orifice still requires the installation to provide standard lengths of straight pipe from the last pipe bend.

Flap Gate: While the analysis is still incomplete, preliminary findings are that flap gates cause negligible back pressure on pipelines that are flowing full. No new interpretations have been developed, pending reactivation to complete the technical note. The difference between low and high speed flow was not significant.

Pipe Flow Control System: Stable flows in secondary canals permit low-cost totalization of flow deliveries to farms because time clocks will suffice instead of complex recorder systems. Known constant flows allow more precise management of irrigation systems. Preliminary indications are that the concept can be made to work. If this proves out, then we should be able to provide economical flow stabilization from main canals to lateral canals.

FUTURE PLANS: End-Cap Orifice: Prepare report.

Flap Gate: Prepare a technical note on the findings that the effects are usually negligible.

Flow Profile Conditioning: Start laboratory study phase and refine test facility, and conduct this study in conjunction with the flow profile study.

Pitot System: The Pitot System reported last year is completed and one report has been published; but a report on the complete data collection and interpretation is still in technical review, and we will continue to follow through to anticipated publication. The control system for constant flow delivery from main canals to lateral canals through pipes will be studied.

REFERENCE: Replogle, J.A. 1999. Measuring irrigation well discharges. Journal of Irrigation and Drainage Engineering. 125(4): 223-229.

COOPERATORS: Maricopa Agricultural Center, Univ. of Arizona (Robert Roth), Wellton Mohawk Irrigation and Drainage District (Charles Slocum), Maricopa-Stanfield Irrigation and Drainage District (Brian Betcher), Global Water (John Dickerman), and Plasti-Fab, Inc. (John Vitas).

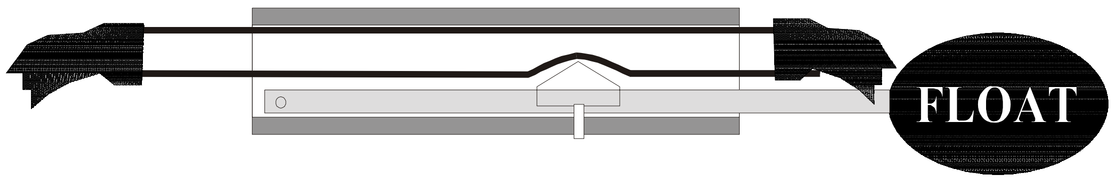

Figure 1. Low-Cost Valve Scheme. Two Valves Requires Per System.

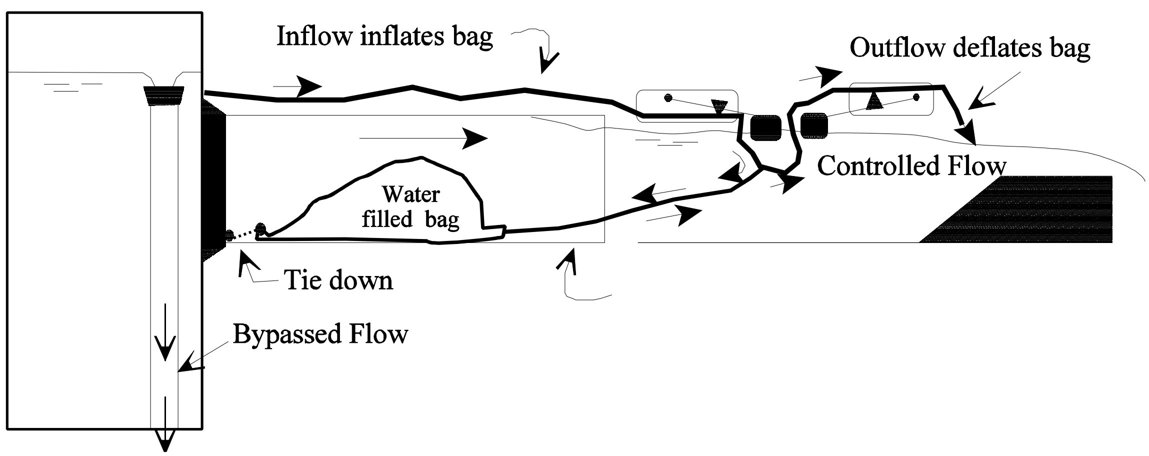

Figure 2. General laboratory set-up for evaluating valve and bag system for flow level control.

FLOW MEASUREMENT WITH FLUMES AND WEIRS

J.A. Replogle, Research Hydraulic Engineer; B.T. Wahlin, Civil Engineer;
and A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEMS: Continuing concerns involve needs connected to open channel flow measurement and control. These include:

Sediment-laden discharges in natural streams are difficult to measure because of sediment movements and accumulations.

Parshall flumes have been popular flow measurement devices for open channels since their introduction in 1926. Traditionally, problems have arisen in Parshall flumes if they are not constructed to specifications. For example, a large Parshall flume installed in California has a field-verified calibration that differs by 10% to 20% from the historical calibrations for that size. This determined difference may or may not be structural.

One of the most important factors in installing a broad-crested weir is vertical placement of the sill. If the sill is too low, the flume may exceed its limit of submergence. If the sill is too high, upstream canal banks may be breached. While this has been partly addressed with the Adjust-A-Flume, simplifications in its construction and adaptation to economical recorders are still needed.

The FLUME3 program does not run well with Windows 95. Cooperative efforts with the USBR to re-code the program for Windows, while nearly complete, have generated some follow-through ideas.

APPROACH: The general objective is to address these problems economically and practically with user-friendly technology.

A prototype self-calibrating flume for sediment-laden flows was designed and installed in northern California (Fig. 1). The objective is to evaluate the idea of the self-calibrating flume system and to determine its operational limitations. The design was based on estimated hydraulic behavior of a chute outlet attached to a "computable" trapezoidal long-throated flume. Two stilling wells, one on the main flume and one on the chute, are expected to provide field calibration for the chute after the main flume no longer can function because of sediment deposits. A laboratory model is part of a thesis study at the University of Arizona to check the limits of sediment handling, the best slope for the chute, and whether the calibration of the chute remains stable after the sediment fills the main flume.

The historical calibrations of a one-fourth scale model of an eight-foot Parshall flume were previously verified. The objective is to develop methods to modify wrongly constructed Parshall flumes to recover their function for accurate flow measurement and to identify construction anomalies that can cause large calibration shifts. The same model will be fitted with a modified entrance and other changes in an attempt to identify causes of calibration shifts that have been noted in a larger Parshall flume.

Compilation of field experiences by users of the commercialized version of the patented adjustable-sill, long-throated flume will be used to advise on expansion of the product line and to evaluate field durability and vulnerability to damage from frost and animals. The objective is to evaluate field installations and to assist in design and materials changes that may be needed to hasten technology transfer.

New software being written to make flume calibration and design software compatible with the computer Windows environment will be user tested, and supplemented with a user manual, either in paper copy, on-line, or CD versions.

FINDINGS: As reported last year, the California Water Quality Control Board used the flume data from last year to demonstrate the severity of the cinibar tailings (mercury ore) problem to EPA. Based on that, emergency super-fund money ($2.5 million) to stabilize the mine tailings was authorized. More data has been collected to verify the initial findings and to evaluate progress in the effectiveness of the clean-up.

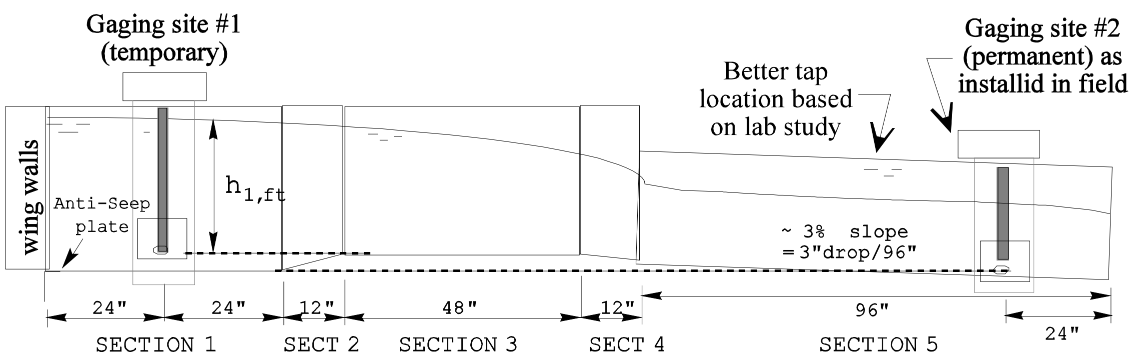

Figure 1. General layout of sediment resistant flume as installed.

With the laboratory model study completed, the PhD student study was successfully submitted to final exam on September 28, 1999. Basically, the sediment (sand) altered the upstream (subcritical) stilling well as predicted. The model indicated that the detection in the chute will provide discharge rates with errors less than 5%. The downstream stilling well in the chute (supercritical) has about the same response with and without sand, as postulated. Findings include that the midpoint of the chute is a more reliable point of depth detection than the point shown on figure 1.

A 50-foot Parshall flume, whose calibration differs from published calibrations by 10% to 20%, has been in operation for nearly 20 years. It has a modified entrance flare that differs from the published rounded entrance. This modification was suspected of causing the calibration difference. Laboratory studies to verify this on a model of a related eight-foot Parshall flume failed to implicate this type of construction anomalies as a cause. Distorted flow entry also was ruled out. Attention now is centered on the published calibration for this size.

Field observations and reports have been compiled for flumes ranging in maximum capacity from 200 gpm (12 l/s) to 35 cfs (1 m^3/s). The users find the devices easy to install and able to meet their operating requirements. The standard versions are now commercially available under the name

"Adjust-a-Flume" (Nu-Way Flume and Equipment Company). Widespread acceptance appears to be growing, as is interest to adding recording instrumentation to the product line that is complicated by the movable reference throat level. Commercial components have been identified that hold the possibility for developing a "kit" to field adjust to many sizes of flumes.

The WinFlume program has been distributed in trial versions to many users, and bugs are corrected when they are found. Current thoughts are for a CD version of a users manual. The format for this has not been firmly decided.

INTERPRETATIONS: The ability to measure flows in heavy sediment carrying flows is important to studies of erosion, runoff, and the effectiveness of best management practices on watersheds. This system expands the range and flume shapes available for such use.

Parshall flumes may not behave as originally specified if installation differs from the standard, or if the flow is distorted at the flume entry. Effects of these problems were evaluated and appear to be of too small a consequence to account for the large errors noted. Therefore, the original calibration may be in question and more definitive model studies may be needed to resolve the questions concerning calibration.

The field problems involving the vertical placement of flumes and broad-crested weirs are greatly reduced for farm-sized earthen channels by the commercialization of a series of semi-portable, long-throated flumes with adjustable throat sills and maximum capacities ranging from 200 gpm (12 l/s) to 35 cfs (1 m^3/s). Sizes above 6 cfs are not intended to be portable. The addition of an instrumentation package will extend the use of the flume systems.

The new flume program will hasten the technology transfer of good flow measuring and monitoring for irrigation management.

FUTURE PLANS: The sediment resistant flume in California will continue to collect data from storm events.. The laboratory model study may be "mothballed" for possible extension studies by another student, which may include development of sediment sampling equipment attached beyond the chute. A second, clear-plastic model is being considered so that sediment movements can be observed more readily in future studies.

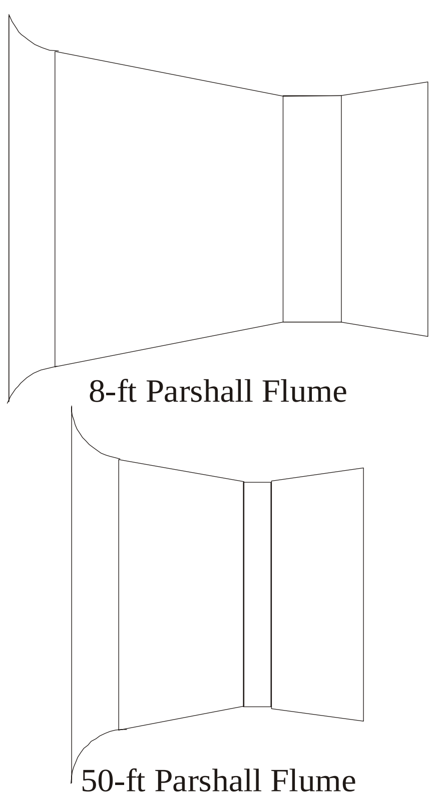

Figure 2. Relative proportions of 8-ft and 50-ft Parshall flumes

The new DACL valve will be laboratory and field evaluated for desired control functions. Further laboratory and field evaluations for function and durability of assembled control systems using the concepts will be reinitiated.

The findings for the field installation of the 50-foot Parshall flume will be further evaluated to see if a calibration shift can be produced, even though the 8-foot Parshall flume, which is not a scale model of the 50-ft version, showed little effects from the usual suspected sources (Fig. 2).

Advice on design changes for adjustable flumes and evaluation of field performance will continue. “Kits” of a possible recording instrumentation system have been sketched that involve minor modifications to commercial equipment and should be available for under $500. This will be continued to see if it can indeed be demonstrated and evaluated.

Write a new book/users manual for the WinFlume Program.

COOPERATORS: Informal cooperation exists among: US Bureau of Reclamation (Tony Wahl, Cliff Pugh, Hydraulics Laboratory, Denver); Natural Resources Conservation Service (Harold Bloom); Imperial Irrigation District (Anisa Divine); Salt River Project (Joe Kissel, Kirk Kennedy); Wellton Mohawk Irrigation and Drainage District (Charles Slokum); Maricopa-Stanfield Irrigation and Drainage District (Brian Betcher); Buckeye Irrigation District (Jackie Mack); Plasti-Fab, Inc.(Randy Stewart); University of Arizona (Don Slack); California Water Quality Control Board (Dyan White); and Nu-way Flume and Equipment Company (Charles Overbay).

WATER REUSE AND GROUNDWATER RECHARGE

H. Bouwer, Research Hydraulic Engineer

PROBLEM: Increasing populations and finite water resources necessitate more water reuse, as do increasingly stringent treatment requirements for discharge of sewage effluent into surface water. The aim of this research is to develop technology for optimum water reuse and the role that soil-aquifer treatment can play in the potable and nonpotable use of sewage effluent. Present focus in the U.S. is on sustainability of soil-aquifer treatment, particularly the long-term fate of synthetic organic compounds (including pharmaceutically active chemicals and disinfection byproducts) in the underground environment. The fate of pathogens and nitrogen also needs to be better understood. In Third World countries, simple, low-tech methods must be used, including lagooning, groundwater recharge, and sand filtration to treat the sewage.

Artificial recharge with infiltration basins for storing fresh water underground as part of integrated water management and conjunctive use of surface water and groundwater, or for underground storage and soil-aquifer treatment (SAT) of sewage effluent for water reuse, is still rapidly increasing. The permeable soils that such systems require are not always available, so that less permeable soils like the loamy sands, sandy loams, and even light loams of agricultural and desert areas are increasingly used to obtain recharge and SAT benefits. Such soils require reliable techniques for infiltration measurements and other pre-investigations to assess the feasibility of the project, and for management of recharge basins to maintain maximum infiltration rates. Climate change is going to be an important factor in future management of water supplies. Because it is impossible to predict it with any accuracy on a local or regional scale, managers increasingly must develop flexible water management schemes so that they can handle excessive as well as inadequate water supplies. This requires more long-term (years to decades) storage of water or "water banking," which is best achieved via artificial recharge of groundwater to avoid the evaporation losses that occur with long-term surface storage behind dams. SAT principles can be extended to river bank filtration systems where wells are drilled at some distance from the river so that river water is "pulled" through the aquifer and receives SAT before it goes to the water treatment plant.

Seepage from ponds, reservoirs, lagoons, wetlands, or other water impoundments often needs to be controlled using earth or plastic linings. Where earth linings are used, the soil material can be placed on the bottom and banks and mechanically compacted when the impoundment is dry, or it can be applied dry or as a slurry to the water itself. The question then is: what gives more seepage control, a compacted soil layer on the bottom where the soil is thoroughly mixed, or a slurry applied to the water where the coarser particles sink faster than the finer particles to create a lining layer that is coarser at the bottom and finer at the top?

Long-term effects of irrigation with sewage effluent on soil and underlying groundwater must be better understood so that future problems of soil and groundwater contamination can be avoided. Potential problems include accumulation of phosphate and metals in the soil and of salts, nitrate, toxic refractory organic compounds, and pathogenic microorganisms in the groundwater. Water reuse is a good practice, but it should not ruin the groundwater. Long-term salt build-up in groundwater will occur in groundwater below any irrigated area (agricultural or urban), regardless of the source water, if there is no drainage, groundwater pumping, or other removal and export of water and salt from the underground environment. Groundwater levels then also will rise, which eventually requires drainage or groundwater pumping to avoid waterlogging of surface soils and formation of salt flats. In urban areas, such groundwater rises will damage buildings, pipelines, landfills, cemeteries, parks, landscaping, etc. The salty water removed from the underground environment must be properly managed to avoid problems.

APPROACH: Technology based on previous research at the U. S. Water Conservation Laboratory (USWCL) and more recent research are applied to new and existing groundwater recharge and water reuse projects here and abroad. Main purposes of the reuse projects range from protecting water quality and aquatic life in surface water to reuse of sewage effluent for nonpotable (mostly urban and agricultural irrigation) and potable purposes. Soil columns in 8 ft x 1 ft stainless steel pipes have been set up in a laboratory greenhouse to study movement of pathogens and chemicals (including exotic organics) in systems involving irrigation with sewage effluent, artificial recharge with sewage effluent, and Colorado River water. Various scenarios of rising groundwater levels and salt buildups due to irrigation were considered and compared with field data to get an idea of rates of rise in groundwater levels and salt content of the upper groundwater, and how to handle this water (i.e., disposal in salt lakes, sequential irrigation of increasingly salt tolerant crops ending with halophytes to concentrate the salts in smaller volumes of water, membrane filtration to remove the salts and allow municipal or agricultural use of the water, and disposal of the reject brines).

The effect of placement of an earth lining in an impoundment for seepage control was evaluated in a laboratory column study using 4-inch diameter clear plastic tubing. At the bottom of each column was an 11 cm layer of silica sand. In column 1, the silica sand was covered with a 16 cm layer of Avondale silt loam at optimum water content to give maximum compaction when packed with a rod. The column was then filled with water and a constant water level was maintained to give a water depth of about 160 cm. The other three columns also were filled with water with the same constant level at the top. Column 2 received the same amount (dry weight) of soil as column 1 but was poured in as a thick slurry at the top of the column. Column 3 also received the same amount of soil as a thick slurry, but was poured in 5 split applications at least 24 hours apart so that the water in the column had become completely clear when the next slurry was applied. Column 4 received the same amount of soil in the same way but in 15 split applications. Seepage rates were then monitored for about 40 days to reach well-defined final values.

FINDINGS: Field and laboratory tests continued to show the usefulness of recharge and soil-aquifer treatment in water reuse. Main issues still are sustainability of soil-aquifer treatment and fate of recalcitrant organic compounds, including disinfection byproducts, pharmaceutically active chemicals, and humic and fulvic acids and other organic compounds that react with chlorine to create new disinfection byproducts. Calculation of the water and chemical balance (including salts) indicates that the drainage or deep-percolation water from sewage irrigated fields will be seriously polluted, especially in dry climates.

The slurry applied earth liners had a fine, slowly permeable layer at the top of each layer. Thus, the integranular pressure below the fine top layers was relatively high since the fine layers “carried” the weight of the water. This produced considerable compaction of the liner for about 2 weeks as evidenced by reduced thickness of the layer and reduced infiltration rates until both became constant at the following values.

	Compacted soil	**1 slurry application**	**5 slurry applications**	**15 slurry applications**
Final thickness in cm	16	21	21	19
Final infiltration rate in cm/day	2.7	1.2	1.0	0.85

The seepage rate for the silica sand alone was 9.6 to 11.1 m/day. Thus, the earth lining was very effective in reducing the seepage rate, especially when applied as a slurry. The biggest percentage of reduction from compacted earth to slurry applied soil was achieved when the total amount of soil was given in one slurry application (56%). Five split slurry applications gave further seepage reduction and so did the fifteen split applications. However, the additional seepage reductions (i.e., 17% and 15%) were not as high as the 56% reduction obtained from a compacted lining to a one-application slurry-applied lining. Thus, segregation of soil particles in the earth lining due to slurry application gave better seepage control than a uniform compacted liner. In practice, slurry applications can be repeated until an acceptable seepage level is reached.

INTERPRETATION: The developments of better technologies or concepts for predicting infiltration rates with cylinder infiltrometers, estimating volumes of water that can be stored underground for water banking, and managing relatively fine textured soils to achieve maximum infiltration for recharge will extend the use of artificial recharge of groundwater to “challenging” soil and aquifer conditions. This will enable water resources planners and managers to benefit from the advantages that artificial recharge offers in conjunctive use of surface water and groundwater, in water reuse, and in integrated water management.

FUTURE PLANS: These plans consist primarily of continuing existing research and of developing new field and laboratory research projects, mostly with universities and water districts, on long-term effects of irrigation with sewage effluent on soil and groundwater. Also, infiltration test plots will be installed to verify concepts of recharge basin management developed for finer textured soils where clogging, crusting, fine particle movement or wash-out wash-in, hard setting, and erosion and deposition can seriously reduce infiltration rates.

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IRRIGATION CANAL AUTOMATION

A.J. Clemmens, Research Hydraulic Engineer; R.J. Strand, Engineering Technician;
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and E. Bautista, Agricultural Engineer

PROBLEM: Modern, high-efficiency irrigation systems require a flexible and stable water supply. Typically, open-channel water delivery distribution networks are controlled manually and are not capable of providing this high level of service. Stable flows can be achieved when little flexibility is allowed since canal operators can force canals flows to be relatively steady. Allowing more flexibility increases the amount of unsteady flow and leads to more flow fluctuations to users.

Most canal systems operate with manual upstream control. With this approach, all flow errors end up at the tail end of the system and result in water shortages or spills. In some canals, supervisory control systems are used to try to match inflows with the expected outflows. Because this adjustment is done by trial-and-error, pool volumes and water levels can oscillate until a balance is achieved. In canals with large storage volumes, these fluctuations may have little impact on deliveries. Smaller canals with insufficient storage need more precise downstream control methods than are currently available. Development of improved canal control methods requires convenient simulation of unsteady flow by computer. Many computer models of unsteady canal flow have been built in the last twenty years, some very complex and expensive, designed to model very complicated systems. Only recently have these programs allowed simulation of control algorithms for canal automation.

The objective of this research is to develop technology for the automatic control of canals as a means of improving canal operations. This includes development and testing of canal control algorithms, development of necessary sensors and hardware, development of centralized and local control protocols, refinement of simulation models needed for testing these methods, and field testing of algorithms, hardware, and control protocol.

APPROACH: A Cooperative Research and Development Agreement between ARS and Automata, Inc., was established for the purpose of developing off-the-shelf hardware and software for canal automation; i.e., plug-and-play. We will work closely with Automata in the application and testing of this new hardware and software. The core of this system is the U.S. Water Conservation Laboratory (USWCL) canal automation system that consists of

- feedforward routing of scheduled flow changes (similar to gate stroking),
- feedback control of downstream water levels (to balance canal inflow and outflow), and
- flow control at check structures.

The system is controlled from a personal computer at the irrigation district office. A Supervisory Control and Data Acquisition system (SCADA) is used by operators to monitor the irrigation system and to control gates remotely through radio communications. We plan to use a commercial SCADA package, FIX Dynamics from Intellution, Inc. Standard MODBUS communication protocol will be used to communicate between FIX Dynamics and Automata's Base Station. Eventually all communications in the system will use MODBUS. The USWCL canal control scheme logic (USCWL controller) will be interfaced with FIX Dynamics. The research approach will be to use simulation models to test and further develop various control schemes that can be used within the proposed automation system. The hardware and software components will be assembled and made compatible in the field. Finally, the combined hardware and software automation system will be tested in the field on the WM lateral canal of the Maricopa Stanfield Irrigation and Drainage District.

Simulation of unsteady flow in canals is needed to understand canal pool properties. We routinely use the unsteady-flow simulation package CanalCAD to study canal properties and to test controller performance. The canal properties taken from CanalCAD tests are used within a mathematical analysis software package, MATLAB, to design various controllers. We have been using a centralized proportional-integral controller that include Smith predictors to account for delays (PI+S $_{-}^{+}$). This format allows selection from a series of controllers, including a series of simple local PI controllers. Selection of controllers for testing on the WM canal are based on simulation tests of controller performance on the American Socity of Civil Engineers (ASCE) test cases and simulation of the WM canal itself.

FINDINGS: Poor canal control performance is caused by a mismatch between pool inflows and outflows and/or incorrect pool volumes. Thus, canal controller methods must address control of both flow rates and pool volumes. An understanding of (1) wave travel times and (2) pool volume as a function of flow rate are necessary and sufficient for the development of feedforward control logic, while for feedback control (1) wave travel times and (2) pool backwater surface area can be used.

<u>Simulation studies of downstream-water-level feedback controllers</u>: A comprehensive set of simulation tests was made for ASCE test canal 1. First, for a series of local Proportional Integral (PI) controllers of pool downstream water level, there was little difference between control of gate position or control of flow rate at each check structure. However, use of flow rate control separates control of pools from control of structures. Second, better control was obtained when control actions from one pool were passed upstream to other check structures, invoking the so-called decoupler I. In general, the completely centralized PI controller provided the best performance. The performance of the Smith predictor was mixed. If timing was bad, accounting for delays with the Smith predictor hurt controller performance; while if timing was good, performance improved. A reasonable compromise between controller performance and complexity is to pass a portion of the PI control actions one pool upstream and one downstream. Finally, the integrator-delay model of Schuurmans for defining canal pool properties appears to work very well for controller design.

<u>Development of accurate gate position controller</u>: The canal automation system was installed on the WM canal at the Maricopa-Stanfield Irrigation and Drainage District (MSIDD) using Automata hardware, including Remote Terminal Units (RTUs), gate position sensors, and base station. The RTUs were programmed to move the gate according to the number of pulses requested by the controller and the number of pulses sent from the gate position sensor. This system is functioning very well. Run-on, or gate movement after the motor is turned off, is usually zero and occasionally one pulse. Each pulse represents roughly 0.95 mm, thus we are able to position these gates to within 1 mm. Automata programmed their base station to translate from the MODBUS protocol of the SCADA system to Automata's protocol which is communicated with the RTUs by radio. This communication is functioning, but needs some improvement.

<u>SCADA implementation</u>: The WM canal was set up within the FIX Dynamics SCADA System.

Digital photographs of the canal and the check structures were used as background screens for the SCADA control functions (See Figures 1 and 2). The system was set up to monitor continuously the headgate, all check structures, water levels above two flumes, and water levels at the downstream end of all canal pools. Within FIX, digital signals are sent to the RTU indicating how many pulses to move a gate, and in what direction.

The USWCL canal automation system control program was interfaced to the FIX Dynamics SCADA package. The USWCL control program is a separate program running in parallel with FIX in a Windows NT environment. Information on the state of the system are read from the FIX database by the control program through an ActiveX interface. Control actions determined by the control program are passed to FIX, also through ActiveX. Additional ActiveX elements are used to allow the operator to enter manual changes from FIX screens (for example to move the gate a certain distance rather than pulse (Fig. 2), or to adjust manually water level and check flow setpoints). A first level of error checking was added to the control program so that the controller would not overreact if sensors or communications failed. These were essential during early testing.

Field testing: The control system was made operational and run several times during October 1999. These tests were all run with only the first 5 pools since there were no deliveries downstream. The system functioned as intended. An example of one test run is shown in figure 3. For this test, a simple PI controller was used. The test consisted of starting with the initial water level as the setpoint and gradually raising the setpoint to the desired level. The controller and control program were functioning properly, but had not yet stabilized by the end of the test. Numerous communications and other small problems will require additional RTU, base-station, and control programming to clean up.

INTERPRETATION: The feasibility of a plug-and-play type canal automation system looks promising. Ensuring proper functioning of the system for a given canal will still require some engineering analysis to determine hydraulic properties and controller constants so that the automation performs adequately.

FUTURE PLANS: Communication has been the biggest problem. Assuring that the controller will perform appropriately requires that the control program have some control over the obtaining of information from the RTUs. MODBUS allows this, but it is not programmed into the base-station translator. A better solution appears to be programming MODBUS into the RTU software. This will allow the base-station to control the collection of information rather than relying on FIX's periodic querying. The current RTU programming has unneccessary code that is left over from other Automata applications. We plan to eliminate as much of this unnecessary code as possible and to remove the automatic periodic reporting. Additional features need to be added to the RTU and control programs. Work will continue on the development of feedback and disturbance controllers that perform better under unusual circumstances. Finally, a number of controllers will be tested on the WM canal in real time, which also will serve to test the control and RTU programs.

COOPERATORS: Lenny Feuer, Automata, Inc., Nevada City CA; Gary Sloan, MSIDD, Stanfield AZ; Jan Schuurmans, University of Twente, The Netherlands; Dave Rogers, USBR, Denver; Charles Burt, Cal Poly, San Luis Obispo CA; Bob Gooch, Salt River Project, Phoenix AZ; Victor Ruiz, IMTA, Cuernavaca, Mexico; Pierre-Olivier

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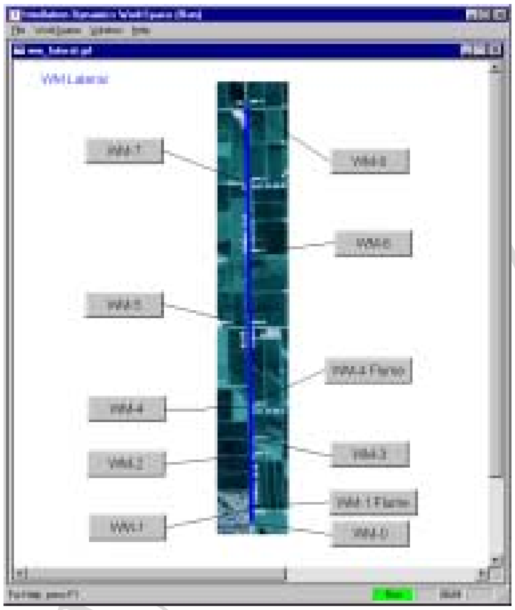

Fig.1. FIX SCADA screen showing WM canal layout.

Fig. 2. FIX SCADA screen of WM-2 check structure, including graphs of water level and gate position and activeX element for changing gate position.

Fig. 3 FIX SCADA screen showing results of test on Oct. 19, 1999. Red lines are water level setpoints and green lines are overflow weirs.

CANAL AUTOMATION PILOT PROJECT FOR SALT RIVER PROJECT'S ARIZONA CANAL

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PROBLEM: The Salt River Project (SRP) is the largest municipal and agricultural water supplier in the Phoenix valley. The district also has a long history of being progressive in the management of its water distribution system. In 1995, SRP initiated an in-house research and development project, in cooperation with the U.S. Water Conservation Laboratory (USWCL), to determine the feasibility of implementing canal automation within its distribution network. Canal automation is expected to improve service, reduce operating costs, and improve SRP's stewardship of resources. The objective of this project is to develop an automated canal control system that is compatible with SRP's current canal operational strategies and systems.

APPROACH: The proposed canal control scheme has three main components: (1) downstream water-level feedback control to handle disturbances or errors in flow rate, (2) open-loop feedforward routing of scheduled or measured offtake flow changes, and (3) check structure flow-rate control. Phase I of this pilot project consisted of the development of an automatic control system and simulation studies to test its ability to control water levels on an SRP canal system reach. The upper portion of the Arizona Canal was chosen as the study site. This section includes 5 pools, separated by check structures, and a major branch point at the heading of the Grand Canal. Findings of this initial phase were reported in Clemmens et al (1997).

In view of the promising results, SRP decided to continue with the next phase. In Phase II of the pilot project, which is currently underway, we are investigating various control system issues identified during Phase I and programming the canal automation system into SRP's computing environment. Specific items that have been under investigation during Phase II are the following:

(1) A computer program has been under development to carry out automatically the the feedforward control calculations.

(2) Analysis of the feedforward control problem was expanded to include the entire Arizona and Grand Canals. The HEC-RAS steady-state hydraulic simulation program was used to determine the hydraulic properties of these canals needed for control system design.

(3) The Arizona Canal system is supplied by a diversion structure with limited storage capacity, Granite Reef. Because of this supply limitation, a feedback control system for the Arizona Canal may require extending the initial control point to an upstream dam. A study was carried out to develop a hydraulic model of the river system that supplies water to Granite Reef. This includes a river reach between Stewart Mountain and Granite Reef on the Salt River and a reach between